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Tropospheric slid Airborne Emission Spectrometers

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I. Introduction

This paper describes the development of two related instruments, the Tropospheric Emission Spectrometer (TIN) and the Airborne Emission Spectrometer (AI'S). Both instruments are infrared imaging Fourier Transform Spectrometers, used for measuring the state of the lower 'atmosphere, and in particular the measurement c f ozone and ozone sources and sinks.

The Tropospheric Emission Spectrometer will fly on the NASA Mission to Planet Earth, Earth Observing System, Chemist] y-1 Platform in 2002. TES will measure the global distribution of ozone and its precursors m the lower atmosphere on a global scale for five years. It will produce, at least once per month, a global survey of the troposphere (from the ground to about 30 km altitude) including the global distribution (with altitude) of ozone, methane, carbon monoxide, nitric acid, nitric oxide and nitrogen dioxide, employing concatenated limb and nadir views. This data will be used to calibrate and update global atmospheric models that are used to evaluate the current state and predict the future state of the atmosphere. '1 ES will also support regional and local data collection activities

The Airborne Emission Spectrometer is an airborne precursor to the tropospheric emission spectrometer. It was completed in 1994, and has completed several data collection campaigns. It is limited to down looking observations of the portion of the troposphere below the aircraft.

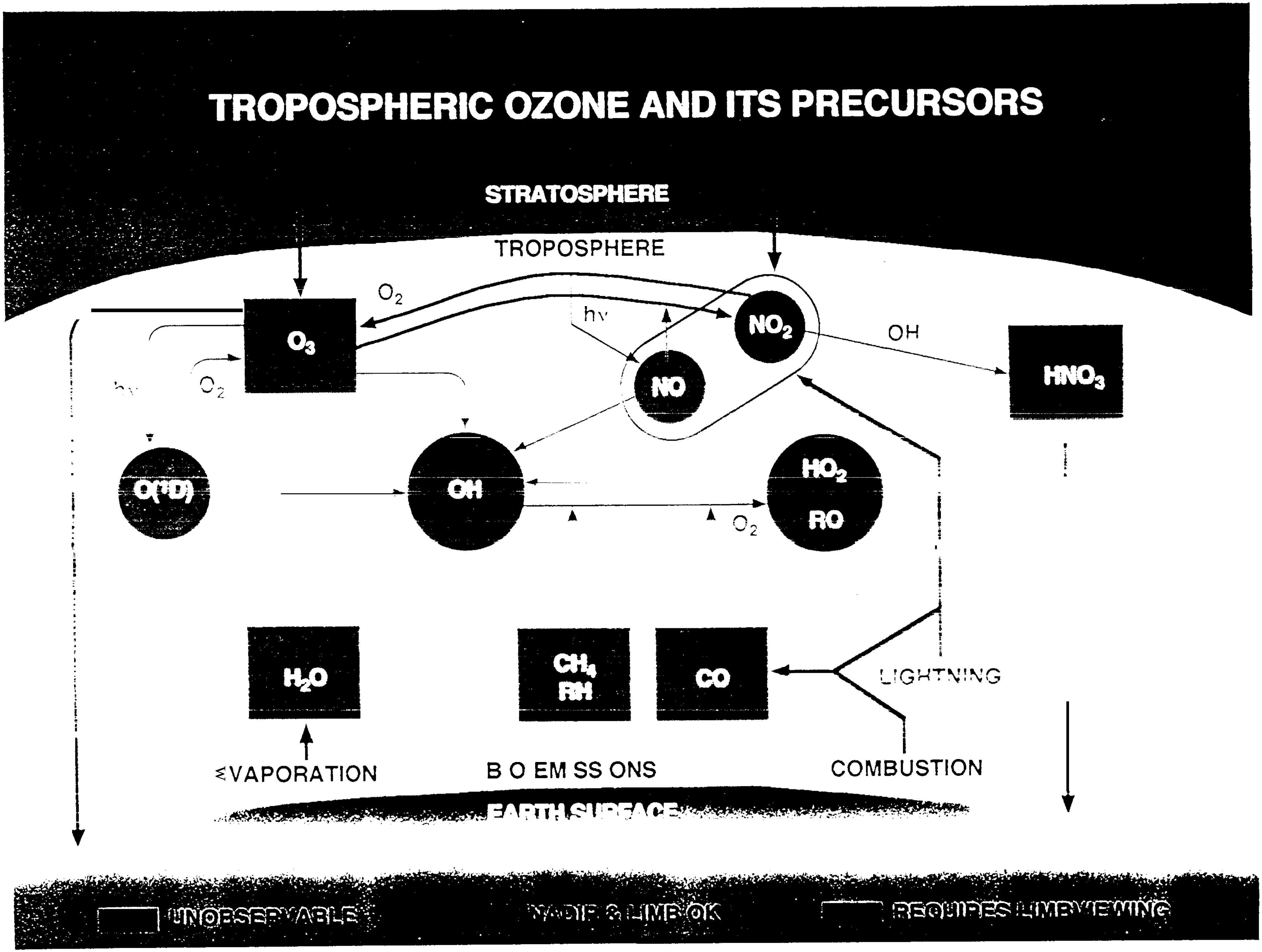
1[. Objectives of the Tropospheric Emission Spectrometer Project

The TES primary objective is the investigation of:

- The three-dimensional distribution of gases important to tropospheric chemistry with particular emphasis on tropospheric ozone: its distribution, production and destruction;
- Troposphere-biosphere interaction,
- Troposphere-stratosill~tl e exchange,

on global, regional and local scales.

Tropospheric ozone, unlike stratospheric ozone, is increasing. Tropospheric ozone is important because it is the primary source of OH radicals on the lower atmosphere. OH is, in turn, impel-trmt because it is through reactions with species such as CO and volatile organic compounds that the atmosphere rids itself of pollution. Unfortunately ozone is itself a pollutant, being a primary ingredient of photochemical smog in urban areas and, furthermore, is a phytotoxicant that directly attacks vegetation. It is therefore very important to understand all the processes through which tropospheric ozone is formed, transported and destroyed. Figure 1


TROPOSPHERIC OZONE AND ITS PRECURSORS
STRATOSPHERE
TROPOSPHERE
O_2
hν
O_3
NO_2
NO
OH
HNO_3
O_2
$O(^1D)$
OH
HO_2
RO
O_2
H_2O
CH_4
RH
CO
LIGHTNING
COMBUSTION
VAPORATION
B O EM SS ONS
EARTH SURFACE
UNOBSERVABLE
NADIR & LIMB OK
REQUIRES LIMB VIEWING

FIG

shows some of these pathways, including the crucial role of the active. nitrogen species NO and N02. It will be noted that some of the species (such as OH itself) are unobservable by passive remote sensing techniques and others (such as the active nitrogen species) require the extra path-length provided by limb viewing to obtain adequate sensitivity. Hence TES has been designed to make measurement s both in the nadir and at the trailing limb. AES, for simplicity, is limited to near nadir viewing.

III. TES Science Requirements

The gases identified in Figure directly to the instrument science and measurement requirements. The instrument needs to be able to look in both the nadir and limb directions. The nadir views are required for good geographical measurement of boundary layer gas distribution. The limb view is required for measurement of the vertical distribution of ozone, the measurement of stratospheric-tropospheric exchange, and the measurement of NO, NO_2 and HNO_3, the most significant ozone precursors. TES needs to have broad spectral coverage that encompasses all of the gases in the figure, and, to have maximum sensitivity, needs to have spectral resolution that matches the spectral lines we are trying to measure. This is 0.1 cm^{-1} down looking and 0.025 cm^{-1} at the limb. The two are different due to pressure broadening in the lower atmosphere.

The only instrument "that will meet these criteria is an infrared imaging Fourier Transform spectrometer. Table 1 lists the key instrument science requirements.

Table 1 Key TES Science Requirements

Spectral Coverage	650-4350" cm^{-1} (?3 - 15.4 microns)
Spectral Resolution	0.1 cm^{-1} nadir, 0.025 cm^{-1} limb
Spectral Accuracy	0.00025 cm^{-1}
Spatial coverage	45° cone from nadir, rear limb view
Spatial resolution	7.5 x 75 mrad nadir 0.75 x 7.5 mrad limb
Temporal Coverage	global survey> once per month ,
Dynamic Range	cold space to 340 K
Radiometric accuracy	1% radiance (NIST Traceable)
Signal to Noise Ratio	Source Photon shot noise limited

IV. Mission Design

TES produces a global survey of the atmosphere once every month as a standard product. The standard product consists of three levels of data: Level 1, consisting of geographically located, radiometrically calibrated, infrared spectra of the Earth's surface, troposphere, and lower stratosphere in selected frequency bands between 650 and 4350 cm^{-1}; Level ?, geographically located vertical concentration profiles from 0 to 30 km of key tropospheric species, O_3, H_2O, CO, CH_4, NO, NO_2, and HNO_3; Level 3 which consists of interpolated global and regional maps of these species on selected altitude/pressure surfaces. Table 2 lists the TES Standard Products, with expected accuracy and height ranges

Table 2 TES Standard Data Products

EOS Product Number	Product	Absolute Accuracy	Relative Accuracy	Vertical Resolution	Measurement Domain
1616	Temperature Profile	2 K	0.2 K	4 6 km	0-33 km
1325	O_3 Mixing Ratio	N/A	3-20 ppbV	2-6 km	O-33 km
1129	CO Mixing Ratio	N/A	3 15 ppbV	2-6 km	O-33 km
1089	CH_4 Mixing Ratio	N/A	14-40 ppbV	2-6 km	0-33 km
1842	H_2O/HDO Mixing Ratio	N/A	0.5-50 ppmV	2-6 km	0-33 km
1268	NO Mixing Ratio	N/A	20-30 pptV	2-3 km	8-33 km
1278	NO_2 Mixing Ratio	N/A	TBD	2-3 km	4-33 km
1206	HNO3 Mixing Ratio	N/A	3 pptV	2-3 km	4-33 km
2455	Land Surface Brightness	1 K	0.1 K		

Figure 2 shows the TES Global Survey Observational sequence. TES observes in the Nadir first, and then approximately seven minutes later, looks at the trailing limb in the same geographical location as the nadir survey. The Global Survey requires four days of observations to produce a map grid of measurements on approximately 500 km centers. Figure 3 shows the details of an observation sequence. The sequence begins with a two-point calibration, using first a view above the Earth's limb, and then with a view of an internal black body Two nadir interferogram sets follow-the calibration, and these in turn are followed by three limb interferogram sets.

V. Instrument Design

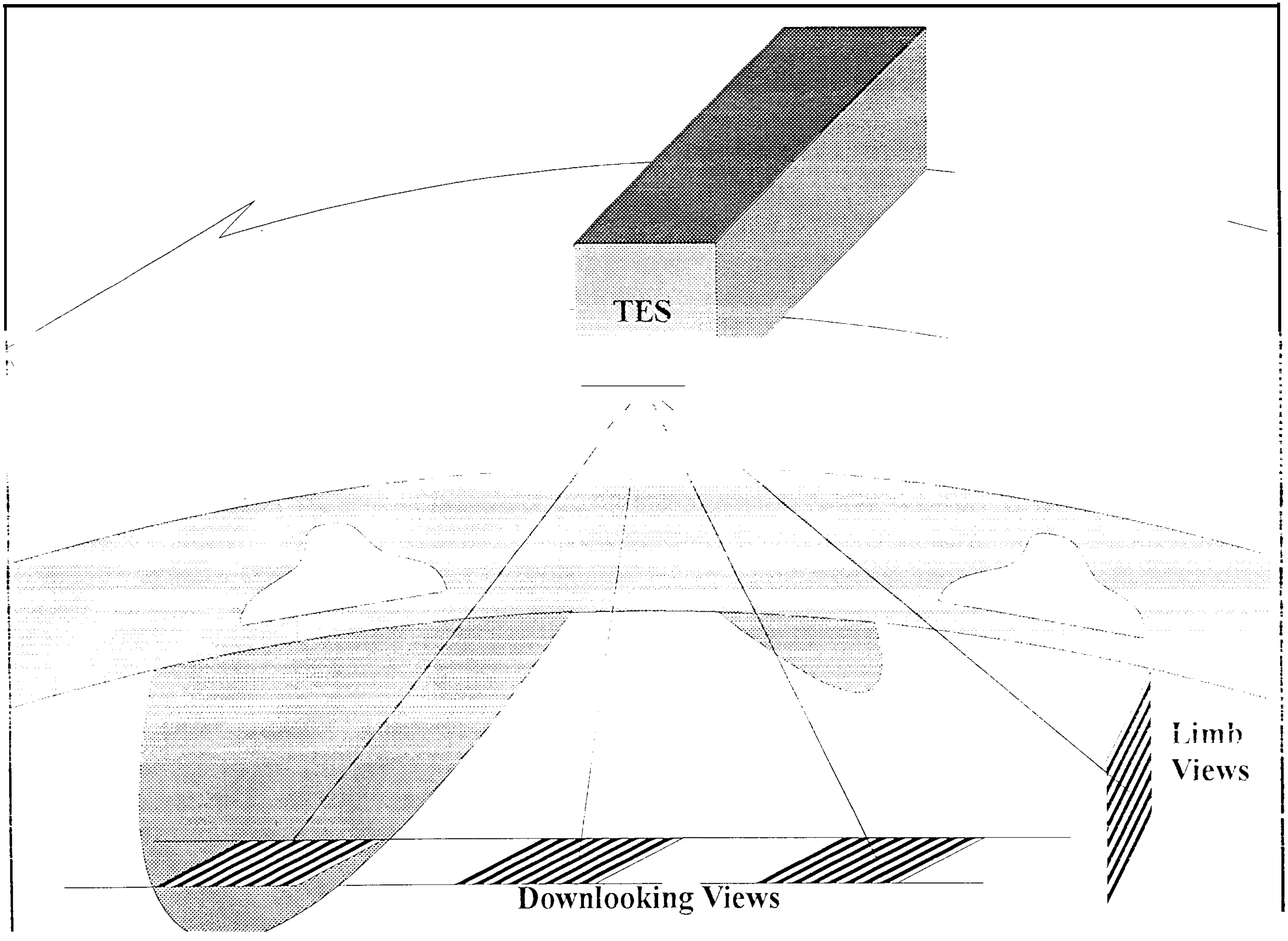


Fig. 2: Cartoon of TES Data Acquisition

FIG 2

NADIR & LIMB GLOBAL SURVEY STRATEGY

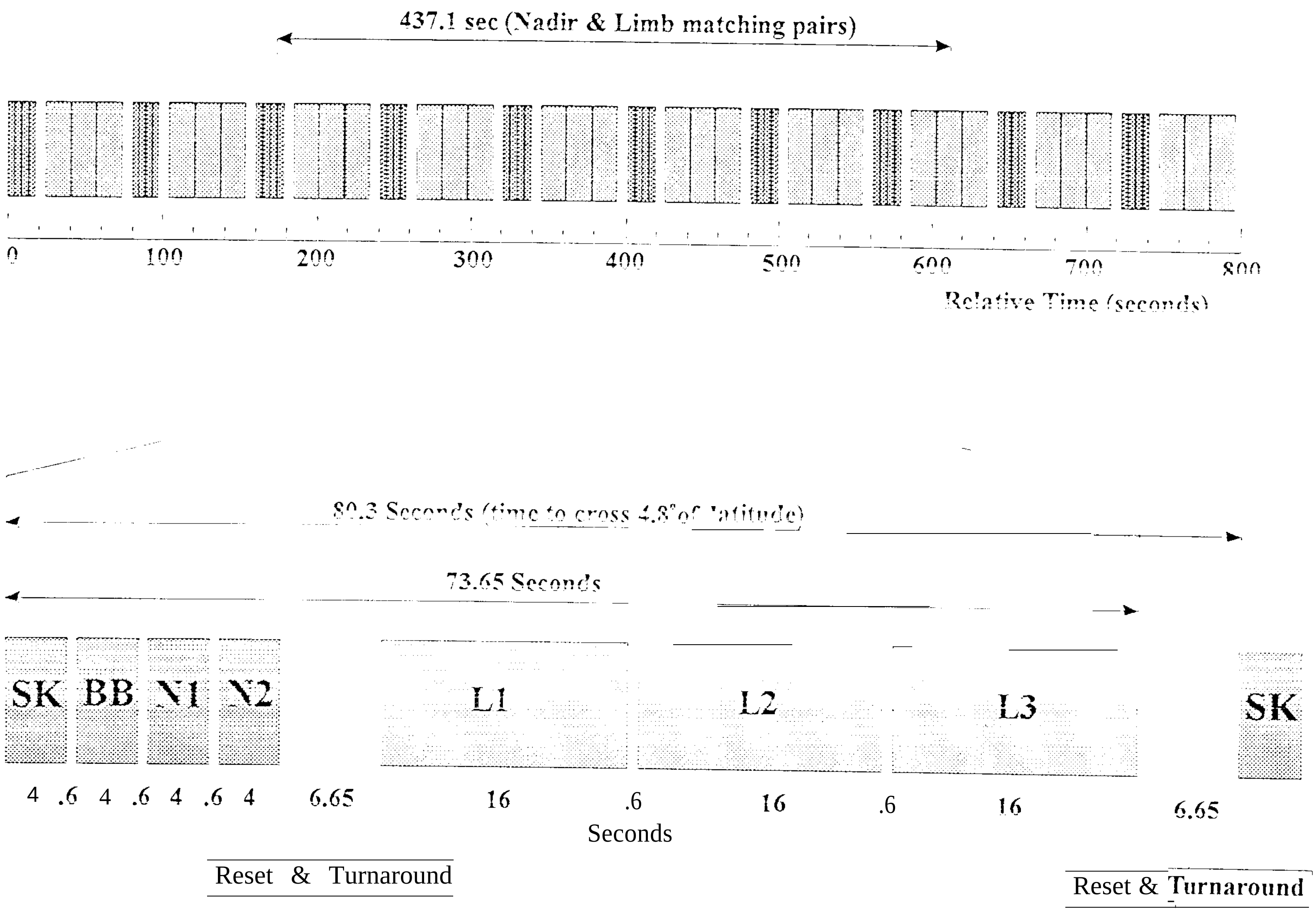


FIG 3

TES Functional Block Diagram

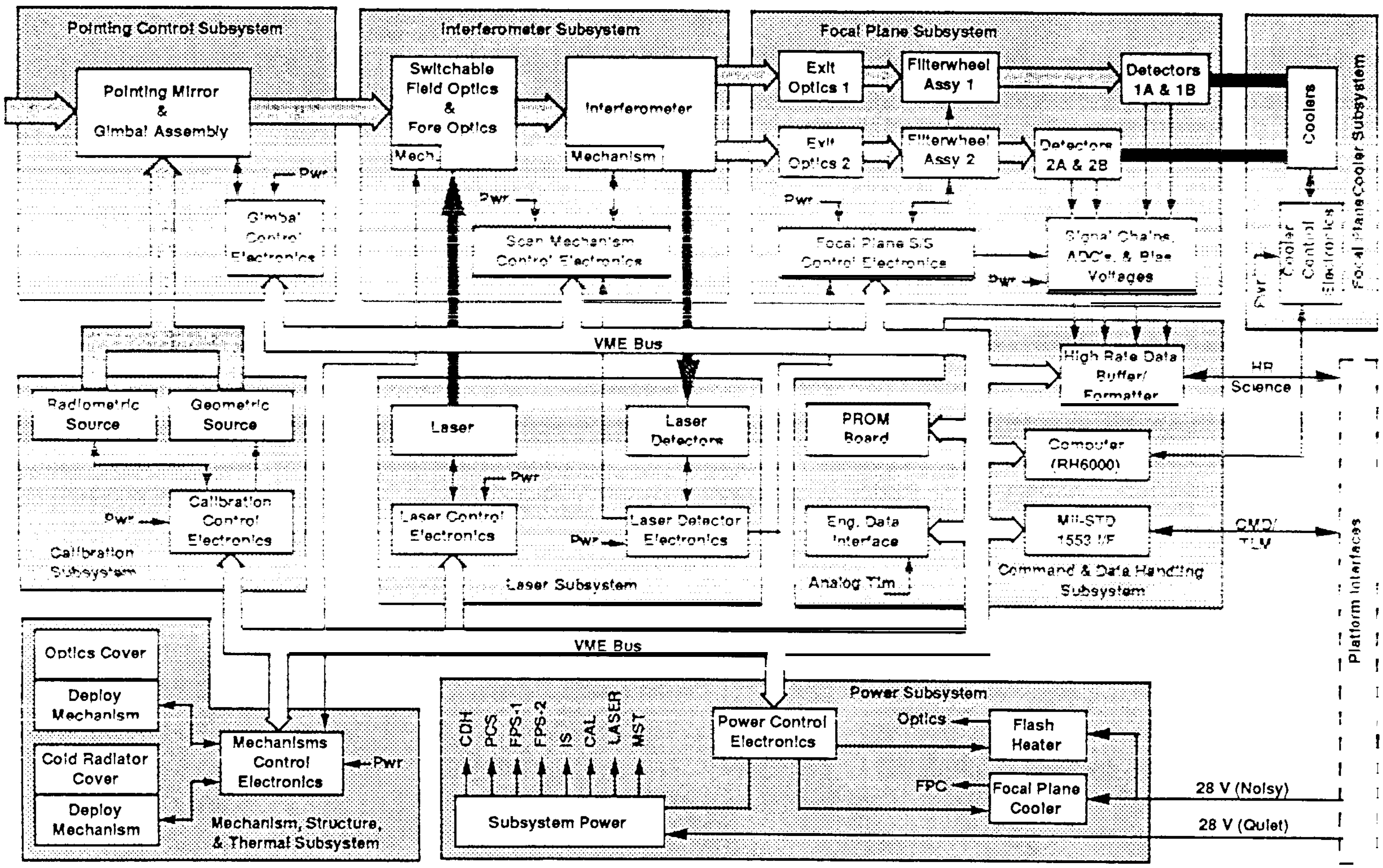


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Fig 4

TES INSTRUMENT
SECTION C-C

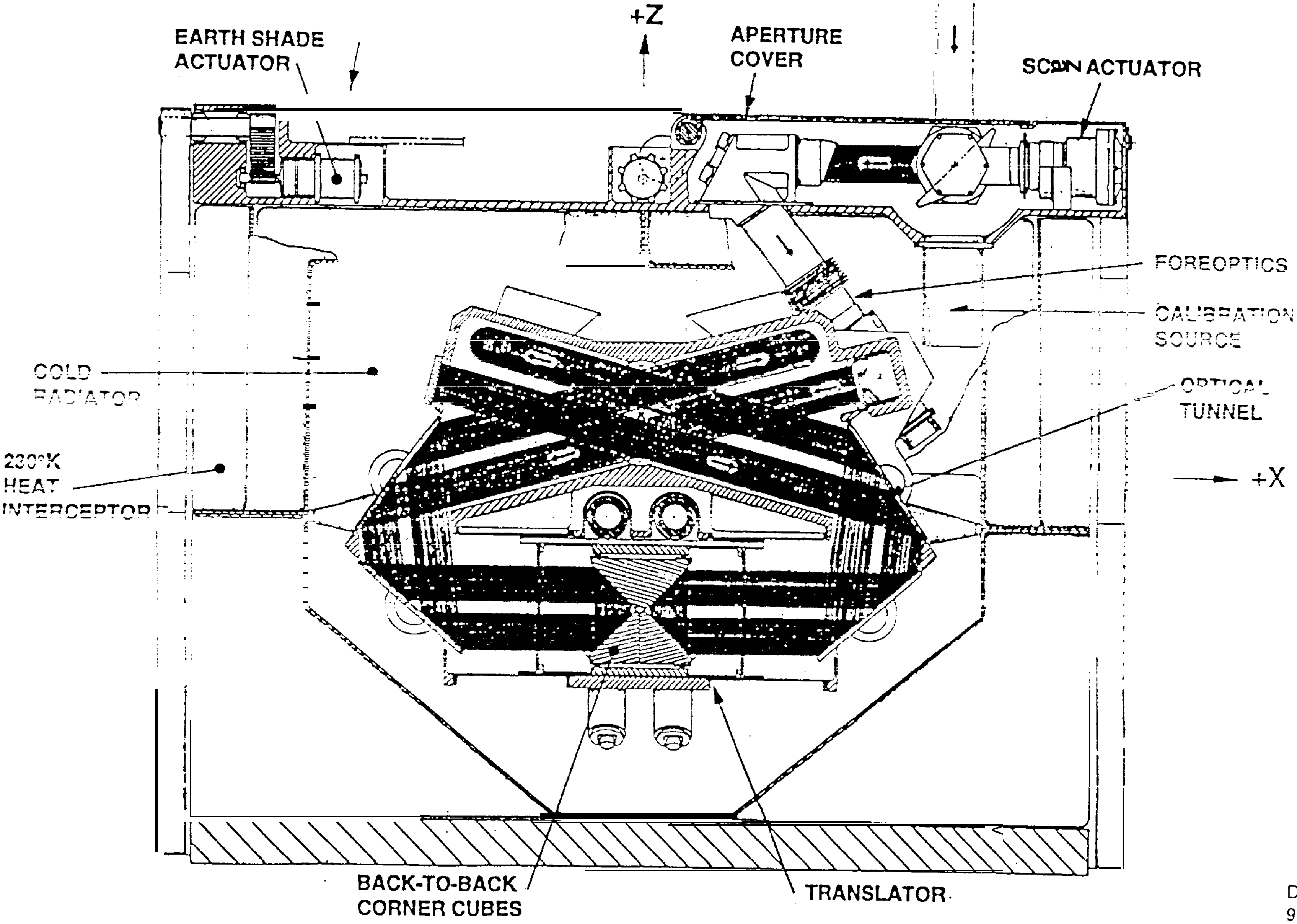

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Fig 6

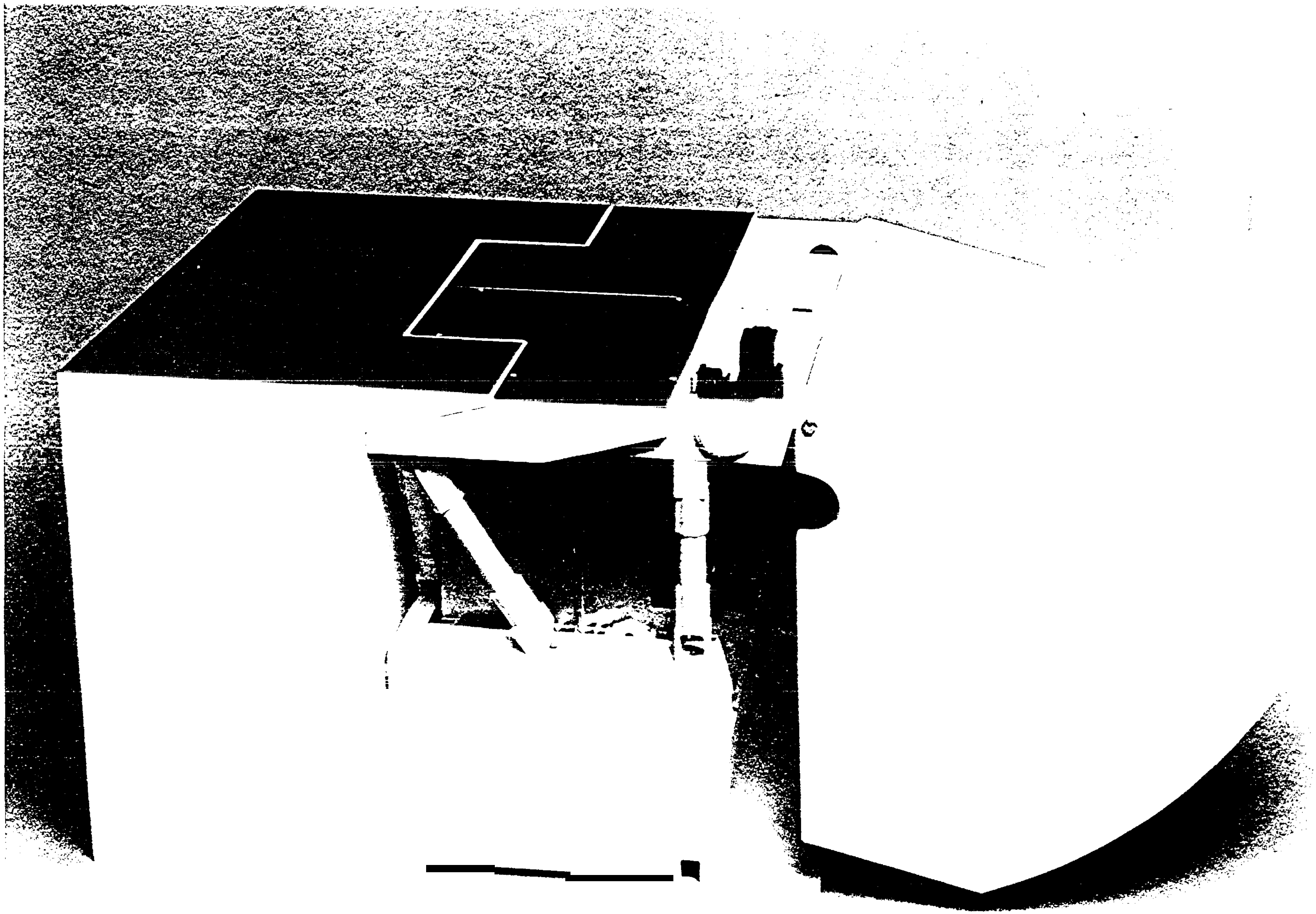


FIG 7

Table 4 TES Optical Filters		
1A5	2800	3050
1A6	4[illegible]50	4250
1B1	820	1050
1B2	950	1150
2A1	1100	1325
2A2	1300	1550
2A3	1500	1750
2A4	1700	1950
2B1	600	900

The focal plane subsystem also includes the signal chains, which consist of a cold focal plane preamplifier, followed by a switchable gain post amplifier, a foll-pole. bandpass filter and an A/D converter.

The Command and Data Handling Subsystem consists of the flight computer and data buffering and format circuits.

The Calibration Subsystem is primarily a high quality black body, with a temperature range of 180 to 350 K, used for radiometric calibration of TES

The laser subsystem is used to measure changes in optical path length and direction in the interferometer. These signals are used to control detector sampling, keeping sampling based on optical path length rather than clock signals. The laser outputs are also used in motion control of the interferometer.

The cryocooler subsystem consists of a pair of coolers, one for each focal plane.

Figure 6 shows a cut-away of the instrument design. The interferometer is cooled by a space view radiator to 180 K. The remainder of the instrument is at spacecraft ambient, approximately 270 K. A radiation shield around the cold optics helps stabilize temperature, and reduces loads on the cold radiator. An earth shield prevents the radiator from seeing earth shine, The top on the instrument has a pair of cooler radiators and an electronics package radiator. Figure 7 shows a mock-up of the instrument.

Table 5 gives the key instrument accommodation parameters

Table 5 TES Instrument Parameters		
Parameter	Value	Units

Table 5 "TES Instrument Parameters

Size (l X W X h)	1 1 x 1 4 x 1	m
Volume	1.65	m^3
Power	300	W
Mass	300	kg
Peak Data Rate	6	MBPS
Average Data Rate (Two Orbit)	4.4	MBPS

VI Airborne Emission Spectrometer

AES is an infrared Fourier Transform Spectrometer intended for the investigation of the chemistry and physics of the troposphere from platforms such as the NASA DC-3 and P-3 research aircraft. AES is complementary to, and, test-bed for, the Tropospheric Emission Spectrometer (TES) which will fly as an element of the Earth Observing System (EOS) early in the next century. As a prototype of the space based TES it is providing critical precursor data on both the acquisition methodology and on regional atmospheric chemistry. After TES is launched, AES will continue to play an important role in correlative measurements through under flight of the EOS spacecraft.

VII. instrument Requirements

The Nadir science requirements of TES and the interface requirements of available aircraft were used to develop a set of detailed instrument requirements.

The aircraft generally available to fly the instrument include the NASA 1'-311 and the NASA DC-8. The P-3B posed the more difficult interface challenges, high vibration levels and an extremely narrow door. (Coping with the design difficulties imposed by the narrow door drove the instrument packaging) All aircraft have high internal vibration and acoustic noise levels when compared to normal laboratory conditions. The instrument was required to be insensitive to aircraft vibration and acoustic noise; to work at a pressure equivalent to 7500 ft altitude, the normal working pressure for high altitude aircraft; to work over a temperature range of 10 to 30 C, and to work after long soaks at higher and lower temperatures, Although no specific numerical requirements for these conditions were imposed, normal aircraft operations can result in the plane being left un-powered over night on a runway, or sitting for several hours, un-powered in the summer sun.

VIII. **instrument Design**

instrument System Design

The instrument system block {Iii:',r;ll is shown in figure 8. The major division of the instrument is a pointing control subsystem and an instrument system

Subsystem Breakdown

Instrument Control is primarily through the instrument control computer, a rack mounted industrial version 486. The instrument operator has access to all instrument temperatures and critical voltages, and has a visual display of the instrument status at all times.

Aircraft Interfaces are kept as simple as possible. The main interface is a power interface to the aircraft power bus. Power converters provide isolation from aircraft bus noise, frequency and amplitude drifts. On some aircraft a data acquisition system collects and broadcasts aircraft data such as altitude, GPS position data, attitude, wind speed, internal and external temperatures, etc. When these data are available, the instrument is capable of collecting and storing it with the interferogram data.

Optical Design

Figure 9 shows the optical design of the main **body** of the instrument. The instrument consists of a Michelson Interferometer, with open, gold coated retro reflectors. A fold mirror is used in the fixed arm to help with instrument packaging. The beamsplitter and compensator are both Potassium Bromide. The beamsplitter has a Germanium coating on the rear surface. The front surface of the beamsplitter and both surfaces of the compensator plate are uncoated. All refractive surfaces in the instrument are wedged. The central **five** mm are coated with gold to provide a good coating for the Nd:YAG laser. The coating thickness was chosen to maximize the beamsplitter efficiency (4RT) over the spectral range. The interferometer vacuum chamber windows are both ZnSe, and both are coated with a broad band anti-reflective coating. All mirrors are gold coated for maximum average reflectivity.

The control laser is a commercial diode pumped Nd:YAG laser (Lightwave Electronics Series 123/1 24) operating at 1.06 microns. It is external to the vacuum chamber for ease in alignment. A central pick- off mirror takes the laser signal to the fringe counting electronics before the main beam is directed to an imaging mirror. After the imaging mirror, a set of dichroic beamsplitters and fold mirrors is used to ensure that all of the detectors are in conjugate image planes. The dewars all contain re-imaging optics that re-collimate and de-magnify the image to match the final detector size. The optical filters are placed in collimated space. Each filter wheel also contains a totally open position, and a totally closed position.

There are several pointing system front ends that can be placed on the instrument, depending on the pointing accuracy required, the field of view required, and the aircraft interface. One has a 5 cm aperture, the other 20 cm. The aircraft window has a 35.6 cm diameter, with a useable aperture of 34.3 cm.

Mechanical Design

Vibration isolation was one of the major design tasks. The chief concern was the conduction of aircraft vibration, and acoustic noise from the aircraft structure into the instrument. A secondary concern was acoustic noise in the air inside the interferometer contributing a noise signal. The method chosen to isolate the interferometer from aircraft structural noise was to isolate the instrument on air shocks. The interferometer is kept at approximately 0.1 atmospheres to minimize any acoustic coupling between the cabin environment, which can have an ambient noise level of90 dB or higher, and the instrument. In addition, vibration damping materials, were placed on all sheet metal surfaces.

The interferometer is lead screw driven. The lead screw supports the drive motor rotor. The motor is a 180-pole motor. Motor rate is controlled by an optical encoder. The motor is capable of moving the retroreflector at 2 1 cm/sec, and reversing the direction of travel in one second.

Pointing Subsystem

The pointing subsystem consists of two video cameras with recorders, a video tracker, a video annotation and a gyro stabilized gimbal, and interface and control electronics. All of the equipment is commercially available, except for the interface and control electronics. There are two video cameras, a wide angle look-ahead camera that looks about 45 degrees ahead of the instrument, and a narrow angle camera that is used as input to a DBA Systems Model 606-4M/C video tracker. The tracker will track on either black or white targets and is capable of RMS pointing error measurement on the order of half of a video line. The tracker error signals are used to control a gyro stabilized gimbal (Fraser-Volpe Model 71 2). A video annotation board is used to place the computer time (GMT) and interferometer scan number on the video signal to allow use of the video signal in determining exactly what the instrument was viewing.

The Narrow Angle Field of' View is about 4 degrees, keeping the video error signal much smaller than the infrared pixel, and minimizing jitter.

Dewar

The Dewars are custom designed to support the focal plane and filter wheels, and maintain them at 65 K for up to eight hours. The upper volume contains a pump manifold, Liquid nitrogen fills an inner chamber, which contains a coarse aluminum foam to ensure good thermal contact with the detector area. Temperatures are controlled to 65 K by maintaining the nitrogen at the triple point which occurs at a pressure of about O 1 atmospheres

A filter wheel is mechanically coupled to the cold volume by a copper cable. The filter wheel stepper motor is external to the dewar, and coupled to the filter wheel by a vacuum rotary feedthrough.

Detectors

The detector parameters are similar to those of' TES, except that only four pixels arc used to reduce costs and data rate, and the pixels are twice as large, reflecting an earlier TES design state. All of the detectors were built from existing mask sets of 8 x 8 arrays of 140 micron pixels on

160 micron centers. 10 achieve the closest approach to the desired 10:1 geometrical aspect ratio, seven pixels were shorted together, producing an approximate active area of 1040 by 140 microns.

Four spectral bands were chosen and dichroic beamsplitters used to separate the bands. The selected cross over points are xxxxx and xxx Each cross over point results in about 100 cm- 1 of unusable spectral space.

The detectors are mounted on carriers, which also contain a dual JFET pre-amplifier for each pixel. The detector carriers bolt to an steel plate, with vacuum grease making a good thermal path between the Nitrogen compartment and the detector The pre-amplifier also operates at 65 K.

Calibration - instrument Calibration was central to the design process. The airborne environment is poorly controlled, and constantly changing, requiring frequent calibrations to compensate for changing instrument offset and drift, and varying instrumental backgrounds. The main calibration source in an Electro-Optical Industries Model B1605DS14 flat plate calibration target. While it would be better to use a cavity calibration target, volume restrictions in the aircraft make it necessary to use the smallest target possible. The target temperature is controlled to 0.01 C, by an internal sensor. Surface temperatures vary during flight by considerably more due to changing temperature and airflow in the aircraft During flight, we typically record spectra at two temperatures, 350 and 280 K. We also have a secondary Ambient Temperature Target, which is aluminum, uncontrolled, and isolated from the instrument and aircraft structure.

During flights a calibration set {)1'5(spectra of the controlled target and the ambient target are recorded every 15 minutes, alternating between the two controlled target temperatures.

Table 6 AES Instrument Parameters

Parameter	Value	Units
Optical Bench (h x w x 1)	100 x [illegible] x 203.8	cm
Control Console (h x w x 1)	137 x 108 x 58.4	cm
Pump Rack (h x w x 1)	137 x 1($X58,4	cm
Optical Bench weight	443	kg
Control Console	144	kg
Pump rack	155	kg
60 Hz Power	32 starting 6 running	A
400117 Power	1[illegible]	A

Table 6 AFS Instrument Parameters		
Mounting	standard seat rails	
ZnSe A/C window	14 x 1	inches

IX. Instrument Operations

Pre-flight Operations - Before Flight Operations, an extensive set of instrumental calibrations are performed. The basic sequence of pre-flight operations is:

1. interferometer Alignment - The interferometer bearings are checked and the lead screw lubricated with a low out-gassing lubricant. The interferometer alignment is checked by using a HeNe laser, and visibly inspecting the center of the fringe pattern at both ends of travel to ensure that the mechanical and optical axes are aligned, and the symmetry of the pattern near zero optical path difference. Small misalignments are readily observed. The Nd:YAG laser is then aligned with the mechanical and optical axes of the interferometer.

2. Pixel alignment and focus - All of the detectors are brought into focus, and co-aligned so the pixels in each detector will see the same angular field.

3. Radiometric Calibration - This consists of an extensive set of spectra taken over the full operating range of the instrument. A flat plate black body is used as a source, with the temperature varied from 180 to 340 K in 20 K increments.

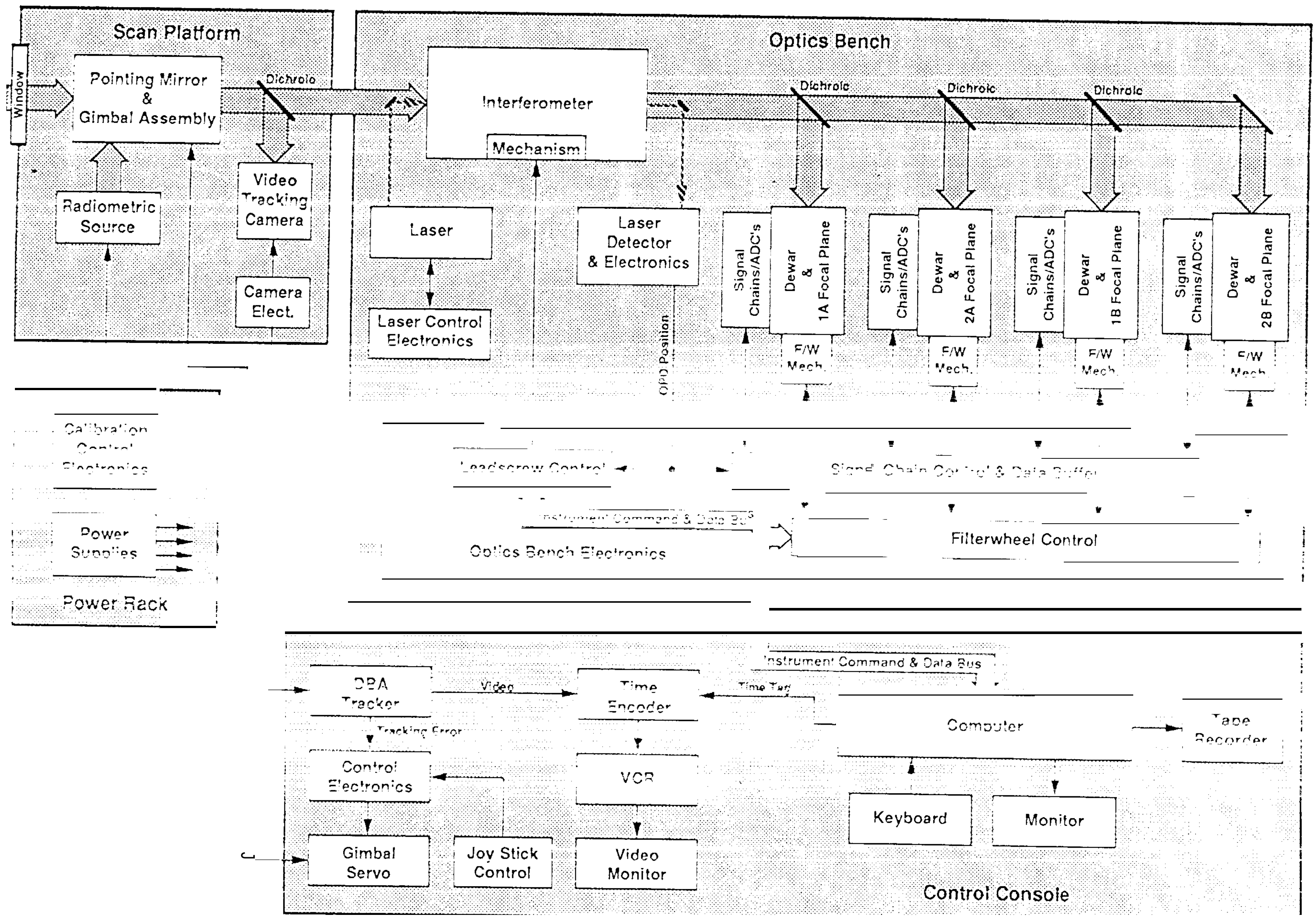
4. Stability - A set of spectra is taken at 350 and 280 K every half hour for a period of five to eight hours. There are instrument drifts in noise equivalent radiance due 10 changes in instrument temperature due to self heating from the instrument electronics.

5. linearity - Three sets of spectra are taken with the black body varying in temperature from 280 to 350 K.

6. Polarization - The instrument polarization is measured by placing a polarizer in front of the instrument and measuring sets of spectra as the polarizer is rotated. There is no measurable instrumental polarization, and this experiment is now repeated infrequently.

7. Spectral Calibration - A gas cell with a known quantity of a llallo~v-lined gas is placed in front of the instrument, and spectra are recorded.

Figure 10 shows the instrument installed on the NASA DC-8. Installation, alignment and check out of the instrument prior to flight generally takes about three days, with the majority of the time going to mechanically attaching the components to the aircraft structure, and cabling into the aircraft power and data system.



ES nstrument Functional Block Diagram

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Fig 8 FIG 8

AES LAYOUT SHOWING DEWARS AND BEAMSPLITTERS IN POSITION

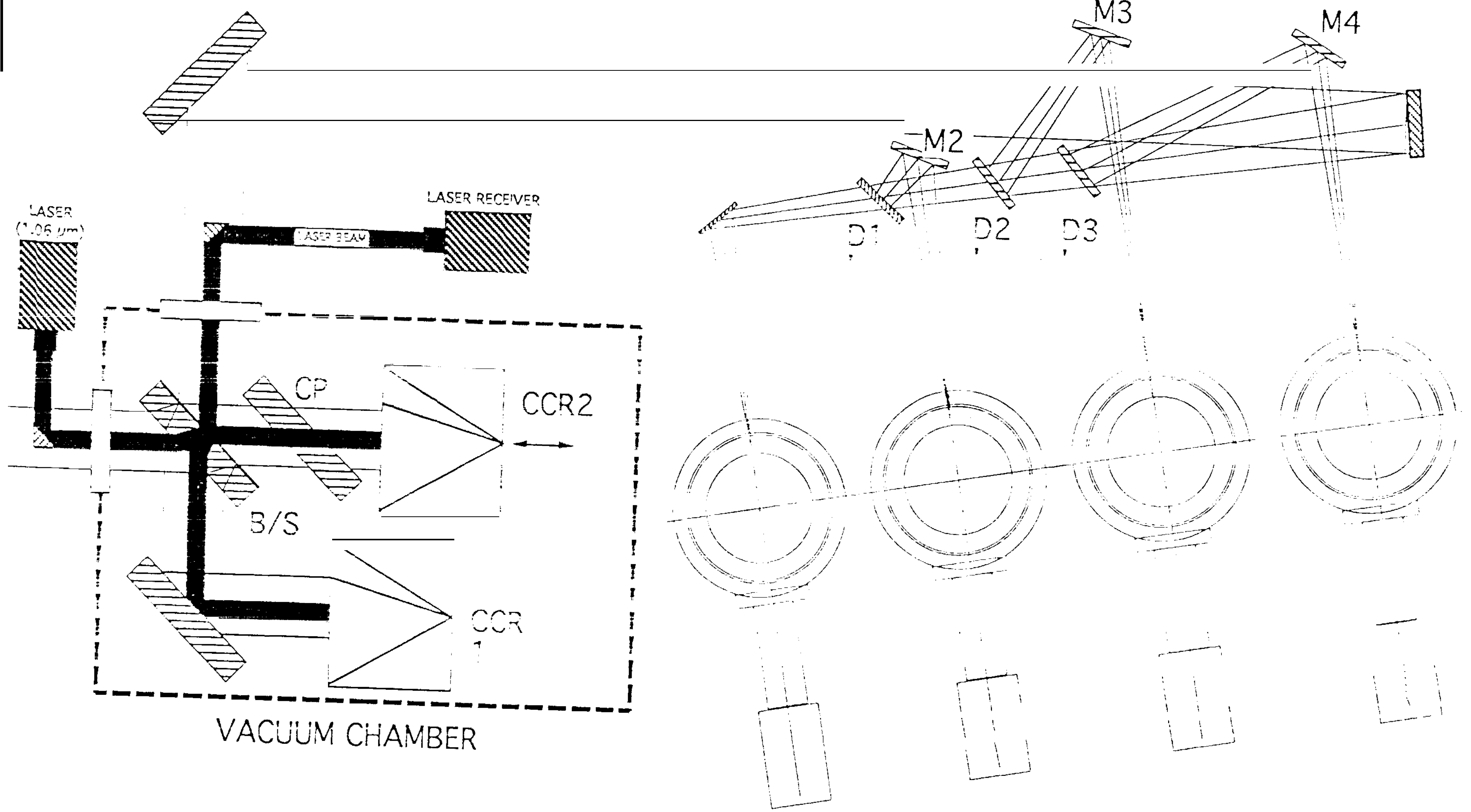
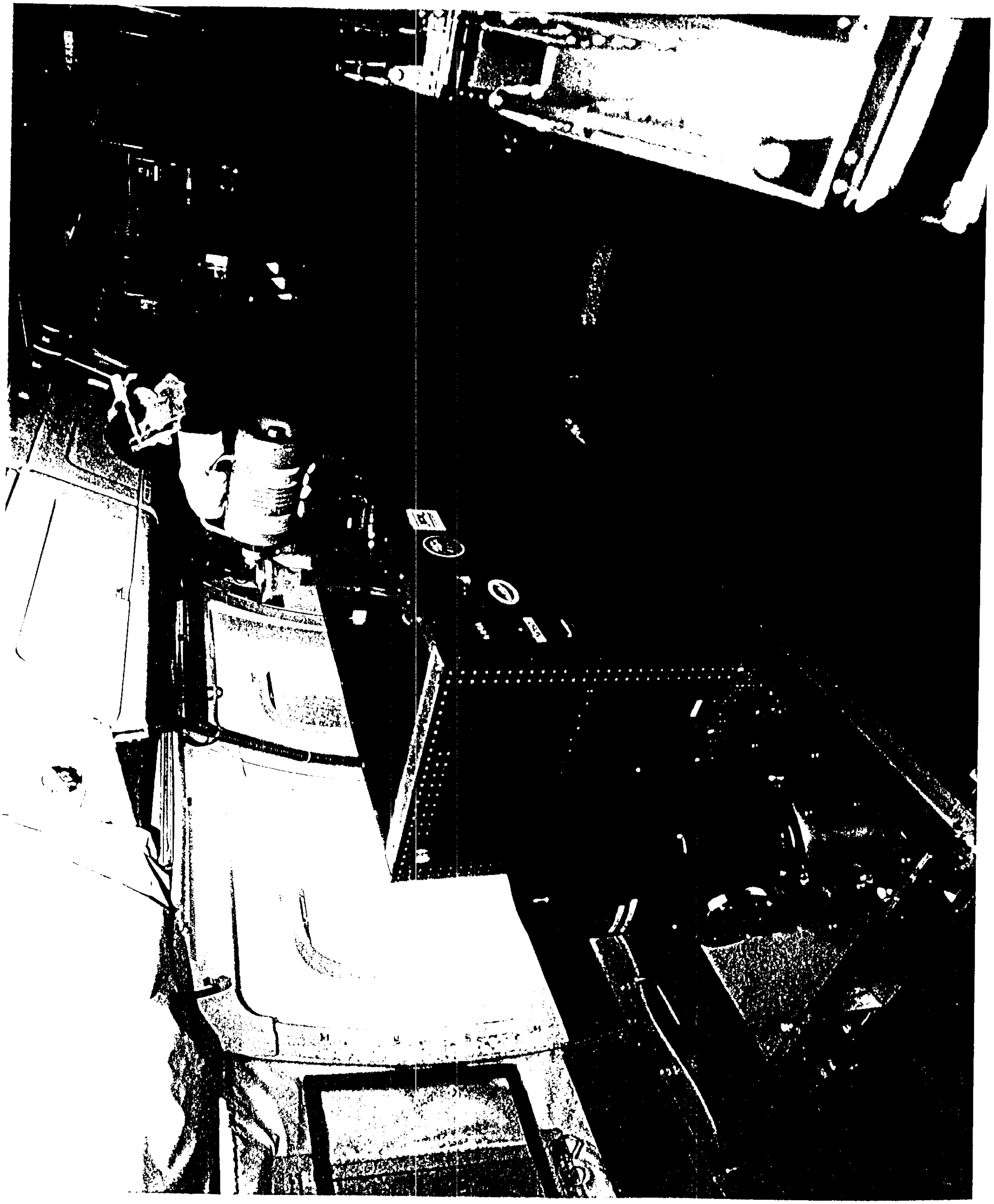


Fig 9



Flight Operations are generally conducted by a three or four-person team. One person operates the pointing subsystem, one operates the instrument and data system, and one records and controls the data collection activities and communicates with the pilot.

X. Acknowledgments

The instruments described in this paper are the work of the Airborne Emission Spectrometer and Tropospheric Emission Spectrometer Instrument and Science Teams. The authors wish to thank all the members of both teams for the extensive support and many contributions to the development of both instruments.

PUT STANDARD JPL ACKNOWLEDGMENT HERE

XI. References